1.0

4.5
5.0

2.8

2.5

3.2

2.2

3.6

1.1

4.0

2.0

1.8

1.25

1.4

1.6

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MEASUREMENT OF IMPEDANCE MISMATCH AND STORED ENERGY FOR RIGHT-ANGLE
REFLECTION OF RAYLEIGH WAVES FROM GROOVES ON Y CUT LiNbO3 *

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ABSTRACT   The Rayleigh-wave reflection coefficient of shallow grooves has been measured on Y-cut LiNbO3 for waves reflected through 90° from the Z into the X direction. As in the case of normal incidence, both impedance mismatch and stored energy contribute to the reflection coefficient, Γ_g. For a shallow groove consisting of a down-step followed by an up-step, $|\Gamma_g| = 2r \sin\theta + \hat{B} \cos\theta$. r is due to the impedance mismatch and is proportional to the step height h while $\hat{B}$ is due to the stored energy and is proportional to h^2. For right-angle reflection, $\theta = (kw+\hat{B})/2$ where $k = 2\pi/\lambda$, and w is the groove width in the propagation direction. Since $\hat{B} << kw$, it follows that r can be measured using grooves of width $\lambda/2$ and spaced by a wavelength λ in the direction of propagation, and $\hat{B}$ can be determined with grooves of width λ spaced by 2λ. The measurements were made at 175 MHz using arrays of 10 grooves ion etched to depths ranging from 600 to 5000 angstroms and inclined at an angle of 46.81° to the Z direction. We find that $r = (.51 \pm .03)(h/\lambda)$. For the energy storage term we measure $\hat{B}/2 = (4.5 \pm .4)(h/\lambda)^2$

Introduction

Arrays of grooves acting as reflective gratings are used in several types of surface wave devices (see Ref. 1 & 2 for reviews). Each edge of a groove, consisting of a down-step followed by an up-step, reflects a fraction of the incident surface-wave beam. For shallow grooves, most of the reflection is due to the mismatch in the Rayleigh-wave fields on the raised and lowered sides of the step, and the reflection-coefficient due to this effect is proportional to the step height, h. For normal incidence this part of the reflection coefficient has been calculated with a boundary-perturbation technique[5] and has also been modeled as an impedance mismatch in a transmission line[5].

Another important contribution to the reflection from a groove is the energy storage at a step discontinuity. The step introduces additional degrees of freedom so that, as the surface wave passes, some of its energy might be thought of as becoming a vibration localized at the vertical edge. For normal-incidence reflection the energy storage has been modeled[5] as a shunt capacitive susceptance connected across a transmission line. This reactive energy is found to add a term quadratic in step height to the reflection coefficient[5] and to decrease the velocity of the surface wave in the grating[6]. Bulk-wave radiation is also produced at a step, but for shallow grooves it seems to be of little practical importance and will not be considered here.

The oblique-incidence right-angle reflection from Z to X on Y-cut LiNbO3 is often used in surface-wave grating devices. A value for the impedance-mismatch part of the reflection coefficient has been reported for this geometry[7]. Although stored energy at the groove edges is an important source of phase shifts in grating devices using right-angle reflection, no measurements of this energy at oblique incidence have to our knowledge been reported.

This paper presents our measurement of the impedance-mismatch and stored-energy contributions to the reflection coefficient for the Z to X right-angle reflection geometry on Y-cut LiNbO3. Because the measurements are performed on grooves rather than single steps, the reflection coefficient of a groove must be derived accounting for both contributions so that the data can be interpreted.

Right-Angle Reflection From a Groove

For an anisotropic medium, the reflection coefficient of a groove Γ_g can be defined as follows:

$$\Gamma_g = \left| \frac{P_{out}}{P_{in}} \right|^{1/2} e^{i\phi} \qquad (1)$$

where P_{in} is the power incident on the groove, P_{out} is the power reflected by the groove, and ϕ is the phase change upon reflection. The usual definition in terms of amplitudes is misleading because the beam width may change and because the relation between power and amplitude is not the same in the two directions. We assume that the equivalent-network model used for normal-incidence reflection[5] applies to the right-angle reflection. Then the expressions for the reflection from an up-step Γ_u, the reflection from a down-step Γ_d, and the transmission coefficient τ (same for up- or down-step) are

$$\Gamma_u = r - j\frac{\hat{B}}{2} \qquad (2)$$

$$\Gamma_d = -r - j\frac{\hat{B}}{2} \qquad (3)$$

$$\tau = 1 - \frac{r^2}{2} - j\frac{\hat{B}}{2} \qquad (4)$$

where r is the impedance-mismatch contribution proportional to the step height, h:

$$r = C\frac{h}{\lambda}, \qquad (5)$$

$\hat{B}$ the energy-storage contribution proportional to h^2:

$$\frac{\hat{B}}{2} = C' \left(\frac{h}{\lambda} \right)^2, \qquad (6)$$

λ is the wavelength of the surface wave, and C and C' are proportionality coefficients to be determined by our experiments. The expressions (2), (3) and (4) result from expansions in which terms of order $(h/\lambda)^3$ and higher are neglected. For weak reflections the $r^2/2$ term in Eq. 4 can usually be neglected although it is of order $(h/\lambda)^2$. The expression for r in (5) has been theoretically derived[3,4] and

experimentally verified [6,7] for normal-incidence reflection from a step on Y-Z LiNbO$_3$. A measurement of this quantity for oblique reflection through 90° was also reported in Ref. 7. $\hat{B}$ as given by expression (6) has been measured [5,6] for normal-incidence on Y-Z LiNbO$_3$ but not for oblique incidence.
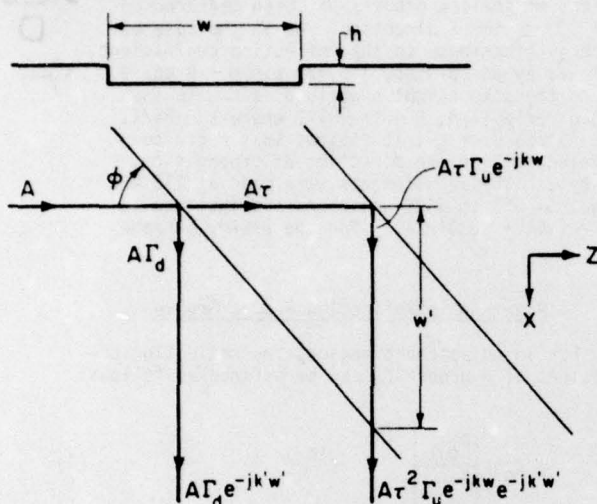

Fig. 1 A surface wave of amplitude A is incident on the two groove edges inclined at an angle ϕ. For a Z-to-X reflection on Y-cut LiNbO$_3$ $\phi=46.82°$. The amplitudes and phases of the parts of the beam reflected from the two edges are indicated. To be consistent with Eq. 1, the amplitude is defined as the square root of the power rather than an actual physical displacement.

The expression for Γ_g can be derived by using Eqs. (2), (3), and (4) in following the surface-wave beam as shown in Fig. 1. Thus,

$$\Gamma_g = \Gamma_d + \tau^2 \, \Gamma_u \, e^{-jkw} \tag{7}$$

The $e^{-jk'w'}$ term is omitted because it merely represents propagation in the X direction. k is the wavenumber in the Z direction and k' in the X direction. Again, neglecting terms of the order $(h/\lambda)^3$ and higher, Eq. 7 becomes

$$\Gamma_g = -2j \, e^{-j\theta} \, (r \sin \theta + \frac{\hat{B}}{2} \cos \theta) \tag{8}$$

where

$$\theta = \frac{kw}{2} + \frac{\hat{B}}{2} \, .$$

Thus, as expected, the only difference between Eq. 8 and the corresponding normal-incidence result [5] is that w/2 enters in θ in place of w.

Note from Eqs. 2 and 3 that the impedance-mismatch reflection alone would have a 180° phase shift between an up and a down step while the energy-storage term would not. Thus if $\theta = \pi/2$ in Eq. 8, i.e., $w=(\lambda/2)(1-\hat{B}/\pi)$ then $|\Gamma_g| = 2r$. On the other hand if $\theta=\pi$, i.e., $w = \lambda(1-\hat{B}/2\pi)$, then $|\Gamma_g|=\hat{B}$. Experimentally, if a surface wave of wavelength λ is reflected from a

grating with groove widths $\lambda/2(\hat{B}<<1)$ and period λ, r is measured. On the other hand, if the width is λ and the period 2λ, $\hat{B}$ is measured. This is the basis of our experiments.
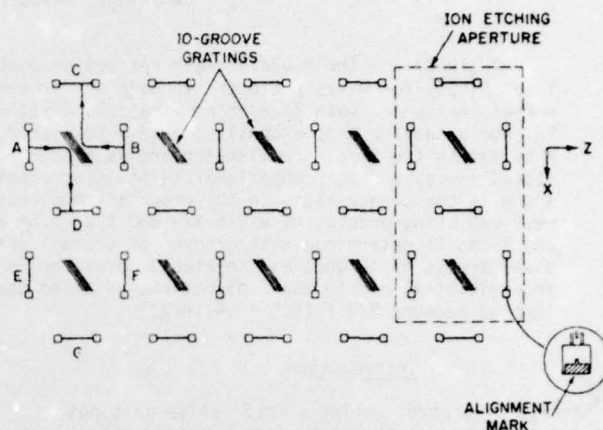

Fig. 2 A schematic of the transducer and grating layout on the Y-cut LiNbO$_3$ surface. After the gratings and alignment marks have been ion-beam etched, the transducer mask is aligned using the transducer pads as shown in inset.

Experiments

Gratings and transducers were fabricated on several Y-cut LiNbO$_3$ crystals as shown in Fig. 2. Each crystal had 10 gratings, ion etched in pairs to 5 different depths, and 27 transducers. On some crystals the gratings had 10 grooves of 10 μm width and 20-μm period as measured in the Z-direction to determine r. On other crystals the gratings had 10 grooves with 20 μm width and 40 μm period to determine $\hat{B}/2$. The transducers had 6 1/2 finger pairs, a center frequency of about 175 MHz, and a beam width of 100λ. The number of grooves was small to avoid multiple-reflection effects.

The ion etching of the groove arrays has been discussed previously [6,8]. The gratings and alignment marks were exposed and developed in 1.5-2-μm thick AZ1350J photoresist. To control the groove width-to-space ratio, w/s, the exposure has to be made with intimate contact between the substrate and the conformable chrome mask as well as the correct intensity. The ion-beam etching was done through an aperture large enough to expose in turn each of the five pairs of gratings in Fig. 2. Depths of etch varied from 600 to 5000 angstroms.

After a set of gratings was fabricated, it was first characterized. The depth of grooves was measured to ±150 angstroms using Mireau interferometry. One crystal was also metallized and Tolansky interference fringes were used to measure the groove depths to ± 40 angstroms. The two methods of measurement agreed. The groove widths and spaces were measured with an optical microscope at 1000X magnification or 1600X with oil immersion in some cases. The values of w/s thus obtained are accurate to ± 3%.

To make electrical measurements, the seven transducers in each section surrounding two gratings (such as A-G, Fig. 2) were connected to 2-mm diameter semi-rigid coaxial cables positioned over the crystal surface. To deduce the reflection coefficient per

groove we assume that the reflection coefficient of the grating of N grooves is N times the reflection coefficient of a single groove. The magnitude of the reflection coefficient per groove $|\Gamma_g|$ was obtained from the electrical measurements in three ways:

1) Impulse response. An incident pulse of one cycle of 175 MHz RF with 5V peak-to-peak amplitude is in turn applied to transducers A and C. Let V_z be the peak of the triangular A-to-B delay-line response, V_x be the peak of the triangular C-to-D delay-line response, and V_R be the peak of the reflected signals, (either A-to-D or B-to-C). Since the transducers have 6 1/2 finger pairs, we have

$$|\Gamma_g| = \frac{2V_R}{6.5 \ \alpha (V_z V_x)^{1/2}} \quad (9)$$

where α is the aperture loss incurred because the projection of each groove on the transducers is less than their full width. In our case $\alpha = 0.82$. (When the period is 2λ, the factor 2 does not appear in the numerator of Eq. 9).

2) CW (long pulse) amplitude response at 175 MHz. A constant, say, 1 μs, RF burst is connected to transducer A (Fig. 2) and an amplitude V_z' is measured at B on a wide-band oscilloscope. Likewise V_x' is measured from C to D. Let V_{R1} be the amplitude measured on the oscilloscope when the signal is reflected from the grating in the path A to D, and V_{R2} be the amplitude measured when the path is C to B. The reflection coefficient of one groove is then

$$|\Gamma_g| = \frac{(V_{R1} \ V_{R2})^{1/2}}{N \ (V_z' \ V_x')^{1/2}} \quad (10)$$

where N is the number of grooves, 10 in our case. If the reflection coefficient does not depend on whether the surface wave is incident on the grating from the left or from the right, then the transducer conversion losses cancel in Eq. 10. In other words, the conversion losses of the two Z-directed transducers do not have to be equal nor do the losses of the two X-directed transducers have to be equal, as is implicitly assumed in writing Eq. 9. (This geometric averaging can in most cases also be used with the impulse response, Eq. 9. An exception occurs if a transducer has several open fingers. The corresponding delay line response is then no longer triangular and Eq. 9 does not apply anyway.)

3) Frequency response. This measurement is similar to the CW above except that the instrumentation is different. Power is measured with a detector and the frequency is swept. $|\Gamma_g|$ is deduced at, say, 175 MHz by arithmetically averaging the A-B and the C-D delay line insertion losses (in dB) and subtracting from the average of the two reflected path (A-D and C-B) insertion losses. Again transducer conversion losses cancel.

Results and Discussion

Measurement of r: Two crystals were fabricated with groove width (measured in the direction of propagation) nearly equal to a half wavelength. The groove width-to-space ratio w/s varied from 1.00 to 1.07. This does not seriously affect our measurements. Substituting the worst case, w/s = 1.07, in Eq. 8 (with $\theta = kw/2$) we get

$$|\Gamma_g| = 2(.9986 \ r - .053 \ \frac{\hat{\beta}}{2})$$

Since the measurements show that $\hat{\beta}/2$ is at least five times smaller than r for the groove depths used, the second term is at most 1%, and we equate $|\Gamma_g|/2$ with r.
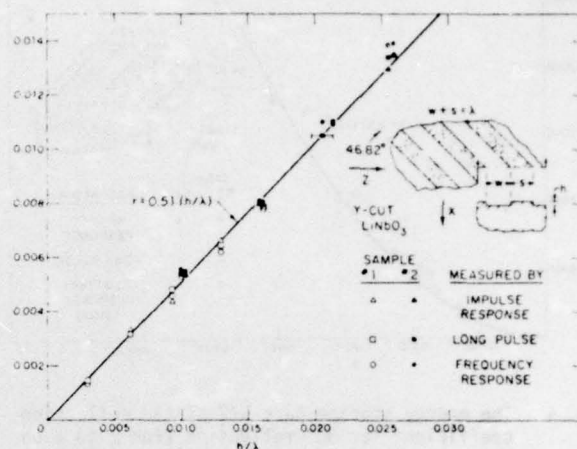

Fig. 3 The impedance mismatch part r of the reflection coefficient of a step for 90° reflection from Z to X on Y-cut LiNbO₃ plotted vs. normalized groove depth. The inset shows a portion of the grating (top view and cross section). The wavelength of 20 μm is equal to the period of the grating in the Z direction. The width of the grooves is equal to half of the wavelength. The slope of the straight line drawn through the points is .51.

Figure 3 shows a plot of the measured values of r vs the normalized groove depth h/λ. A straight line of slope .51 is drawn through the points, thus

$$r = (.51 \pm 0.3) \ (h/\lambda) \quad (11)$$

For the deepest (4900 angstroms) gratings, the loss in signal transmitted through the grating is 3.5% and no longer negligible. The data was corrected for this loss.

Measurement of $\hat{\beta}/2$: Two crystals with groove width (measured in the direction of propagation) approximately equal to a wavelength were fabricated. The width-to-space ratio varied from 1.00 to 1.03, i.e., the departure from 1.00 was barely measurable. Figure 4 shows the measured $\hat{\beta}/2$ plotted vs h/λ. The behavior is seen to be parabolic. By fitting a parabola to the points we determine that

$$\hat{\beta}/2 = (4.5 \pm .4) \ (h/\lambda)^2 \quad (12)$$

Some of the scatter of the points in Fig. 4 is probably due to the fact that w/s is not exactly equal to unity. Plotting $\hat{\beta}/2$ on the vertical axis rather than $|\Gamma_g|/2$ assumes w/s = 1. If w/s = 1.0 ± .02, which the measurement accuracy does not rule out, then $|\Gamma_g|/2 = \pm .031 \ r + .9995 \ \hat{\beta}/2$. For h/λ = .02, the unwanted first term can be as large as 18% of the second $\hat{\beta}$ term.

In fact, measuring $|\Gamma_g|$ when w/s ≠ 1 provides a way of determining the sign of r relative to $\hat{\beta}/2$. A preliminary measurement on a grating with w/s = 1.3, i.e., grooves much wider than spaces shows a reflection coefficient per edge larger than $\hat{\beta}/2$ indicating r has the same sign as $\hat{\beta}/2$. This is also true for normal incidence[5].
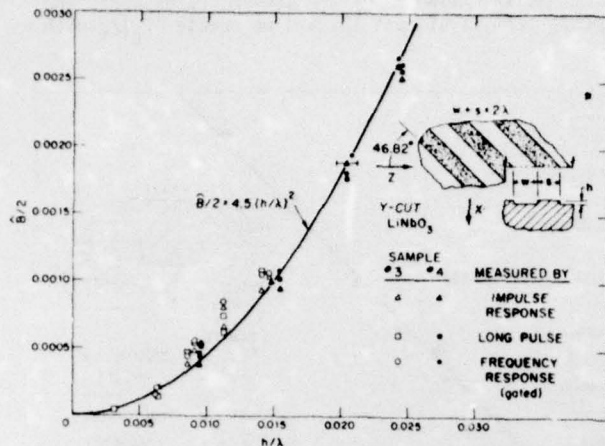
Fig. 4   The energy storage part $\hat{B}/2$ of the reflection coefficient for 90° reflection from Z to X on Y-cut LiNbO₃ plotted vs. normalized groove depth. The inset shows a portion of the grating. The period of the groove grating is two wavelengths in the propagation direction. The width of the grooves is equal to a wavelength, so that the impedance-mismatch contributions from the opposite edges of a groove cancel. A parabola is fitted through the points.

One may wonder whether some of the scatter in the data in Fig. 4 might not be due to variations in groove profile. The photoresist used as a mask in ion etching in our substrates presumably was sufficiently thick to avoid beveling of the groove edges[8,9]. However, a scanning electron microscope examination of one cleaved section through a 3000 angstrom deep grating on sample #1 showed sloping groove edges. This is at present not understood, and deserves more study. From the boundary-perturbation calculations[3] one can show that at normal incidence the fractional decrease in reflection coefficient, r, due to a sloping edge is

$$\frac{\Delta r}{r} = 63\left(\frac{\ell}{\lambda}\right)^2 \tag{13}$$

where ℓ is the length of the slope, i.e., $\ell = 0$ for a vertical edge and $\ell = h$ for a 45° slope. Eq. 13 applies to an isotopic medium. Assuming a 45° slope and taking $\ell/\lambda = .025$, corresponding to the deepest grooves we have used, results in a 4% decrease in r. Thus, if this normal incidence result also approximately holds for the 90° reflection, the sloping edge would lead to variations in r which are within our experimental error.

Summary

All of the data available on the reflection coefficients of grooves in Y cut LiNbO₃ are summarized in Table I. For the same depth, the impedance-mismatch reflection coefficient r is seen to be larger for 90° reflection than for normal incidence whereas the energy-storage contribution $\hat{B}/2$ is 4 1/2 times smaller for the 90° reflection than for normal incidence.

Since the transmission coefficient can approximately be written as follows[5] $\tau \simeq \exp(-j\,\hat{B}/2)$, $\hat{B}/2$ is

directly the phase shift per groove edge. This is important, for example, in understanding and compensating for phase shifts in reflective-array devices.

TABLE I

Reflection coefficients of groove edges on Y-cut LiNbO₃: $r = C(h/\lambda)$, $\hat{B}/2 = C'(h/\lambda)^2$

90°, Z to X Reflection		180°, Z to Z Reflection (normal incidence)	
C	C'	C	C'
.44 to .46 (ref. 7)		.33 (ref. 6)	21 (ref. 5 or 6)
.51 ± .03	4.5 ± .4	.33 (ref. 7)	

Acknowledgements

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